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# B Physics at CDF

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# B-PHYSICS AT CDF*

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**Abstract**

B-physics with $p\bar{p}$ collisions at CDF is reviewed. We discuss production cross sections (including quarkonia), masses, and decay properties (e.g. branching ratios, polarization, lifetimes, and mixing). Notable recent results include reconstruction of $\Lambda_b \rightarrow J/\psi\,\Lambda^0$ with a mass of $5623 \pm 5 \pm 4$ MeV/c$^2$, and $B^0$-mixing measurements with improved precision.

## I. Introduction

B-physics at the Fermilab $p\bar{p}$-collider ($\sqrt{s}$ of 1.8 TeV) is an arena of special interest by virtue of the large cross section: at a luminosity of $10^{31}$/cm$^2$/s b-quarks are produced at $\sim 300$ Hz. Unfortunately this still corresponds to only about one interaction in a thousand. Furthermore, and unlike LEP, the typical b-quark $p_t$ is only a few GeV/c, making it difficult to select b's out of the large background. Despite this handicap, a broad range of topics may be studied: from QCD tests of heavy quark production, to the properties of b-hadrons (masses, lifetimes,...), and finally to the more exotic areas of $B^0$-mixing and eventually to CP-violation studies.

The large backgrounds are suppressed by relying on the feature that heavy quarks produce relatively high $p_t$ leptons, either through semileptonic decays or via decays involving $\psi$'s or $\Upsilon$'s (which decayed into dileptons). The triggers used in the analyses presented here are, basically:

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– $\mu$: $p_t > 7.5\, GeV/c$; – $e$: $E_t > 8.0\, GeV$;

– $\mu\mu$: $p_t > 2.0\, GeV/c$; – $\mu e$: $p_t(\mu) > 2.0\, GeV/c$ $E_t(e) > 5.0\, GeV$.

The implementation of the triggers[1,2,3], as well as details of the CDF detector[4] are described in detail elsewhere; we only note that the detector now includes a Si-$\mu$vertex tracker (SVX)[5] which is capable of discerning displaced b-decay vertices. Several strategies are employed for b-identification: secondary vertices, high $p_t$ leptons, $J/\psi$'s with a displaced vertex, semi-exclusive reconstructions via lepton+D, and full exclusive reconstruction of $J/\psi + X$.

The current series of collider runs ("Run Iabc") started in 1992 and will continue into early 1996. The CDF analyses presented here span integrated luminosities from $\sim$ 15–115 pb$^{-1}$, with final data data sets around 120 pb$^{-1}$. The b-analyses span a wide range of topics and space-time limitations will not permit a full accounting here.

## II. Heavy Quark Production

The production of heavy quarks in hadron colliders provide an important testing ground for perturbative QCD. The top quark opens up a new window in this area, but such data will remain sparse for some time and detailed studies are limited to charm and bottom. CDF has measured b-cross sections (and production correlations) by several different means: statistical impact parameter separation of b's in inclusive jet events[6]; $\mu$-$b$ (correlated) cross sections[7]; $\mu$-$\mu$ (correlated) cross sections from b's[6]; semi-exclusive reconstruction of B-mesons by identifying lepton+D (i.e $B \to \mu D^{(*)} \nu X$, $D^{(*)} \to K^{\mp}\pi^{\pm}(\pi^{\pm})$)[1,6]; and exclusive B-reconstructions ($B \to J/\psi K^+$ or $J/\psi K^{*0}$)[8]. Each technique has its own complementary range in $p_t$ and statistics, as well as varying specificity of the produced hadron (generic b-hadron vs specific B-meson).

These analyses cover $\sim$ 20 pb$^{-1}$ and have either been published[7,8] or extensively reported in past conferences[6] and are not discussed in detail here. However, an example of our B-meson cross section is shown in Fig. 1a. The results are in reasonable agreement with the shape calculated from next-to-leading order QCD[8,9,10], but the data are systematically higher. This appears to be a general feature of our measurements. There is some freedom to play with scale parameters to obtain better agreement, but in conjunction with measurements by D0[11] and UA1[12] ($\sqrt{s}$ of 630 GeV) one is still left with a discrepancy[13]. Possibly there is an unaccounted for growth (within NLO QCD) in the cross section as $\sqrt{s}$ rises, or an unknown systematic in one or more of the experiments. In order to help resolve this question we are now analyzing data taken in a special run at $\sqrt{s}$ of 630 GeV.

In addition to the usual B-mesons, we have searched for the production of the $B_c^{\pm}$ via its decay into $J/\psi\, \pi^{\pm}$. In 75 pb$^{-1}$ no signal was observed in the mass range 6.1–6.4 GeV/c$^2$. The 95% C.L. limit is expressed in terms of the ratio $\sigma_c \cdot B(B_c^{\pm} \to J/\psi\pi^{\pm})/\sigma_u \cdot B(B_u^{\pm} \to J/\psi K^{\pm})$ to reduce the systematic uncertainties; and is shown in Fig. 1b as a function of the unknown

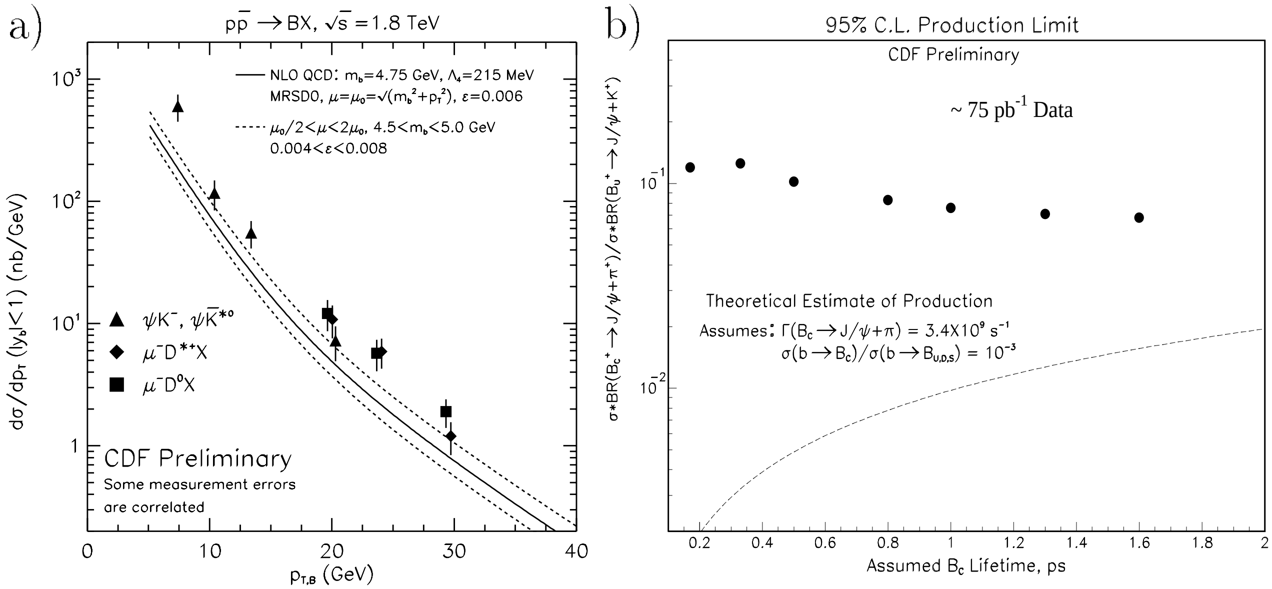


Figure 1: a) B-meson cross section for exclusive and semi-exclusive reconstructions compared to NLO QCD[8,9,10] (dashed lines indicate the range corresponding to variations of QCD parameters). b) Limit on $B_c$ production as a function of lifetime compared to a theoretical estimate[14].

$B_c^{\pm}$ lifetime. A search is also underway in the higher rate semi-leptonic mode $B_c^{\pm} \to J/\psi\, \mu^{\pm} X$.

We also study heavy quark production in the special venue of quarkonia production[15]. We have recently published[16] differential cross sections for production of the individual $\Upsilon$ 1S, 2S, and 3S states via their decays to dimuons from $\sim 17$ pb$^{-1}$. Our measured total cross sections are in modest disagreement ($\sim 2\times$ higher) with NLO color-singlet calculations[17] (including $\chi_b \to \Upsilon\gamma$), although for high $p_t$-Upsilons the data are more like $\sim 10\times$ larger.

B-cross sections may also be measured via $B \to \psi(\textit{non-prompt})X$. It was commonly[9,18,19] presumed that at high energy hadron colliders $J/\psi$'s were mostly from radiative $\chi_c$ and B decays, and $\psi'$'s were almost entirely from B's, i.e. direct $J/\psi$ and $\psi'$ production was small. We tested this belief by using the Si-$\mu$vertex to measure the spectrum of $\psi$-vertex displacements and fitting for prompt, non-prompt, and background fractions[20]. As seen in Fig. 2a ($\sim 18$ pb$^{-1}$) the non-prompt $\psi'$ cross section (circles) is systematically a little higher than a NLO QCD calculation from B's (solid line); but the prompt $\psi'$ component is about $50\times$ higher (solid squares vs dash-dotted lines), in stark disagreement with the NLO color-singlet calculation. A discrepancy was also apparent for prompt $J/\psi$'s[20], but to a much smaller degree. The issue was confused by the large prompt contribution from $\chi_c$'s. We recently reconstructed $\chi_c \to J/\psi\gamma$ and separated out this contribution[22]. Fig. 2b shows $d\sigma/dp_t$ for the $J/\psi$'s from $\chi_c$'s, which agrees well with calculations; and the "direct" $J/\psi$'s (solid squares) that come neither from $\chi_c$'s nor $B$'s, again a striking disparity with theory (dashed line).

The dramatic discrepancy of the direct $\psi'$ cross sections prompted considerable theoretical

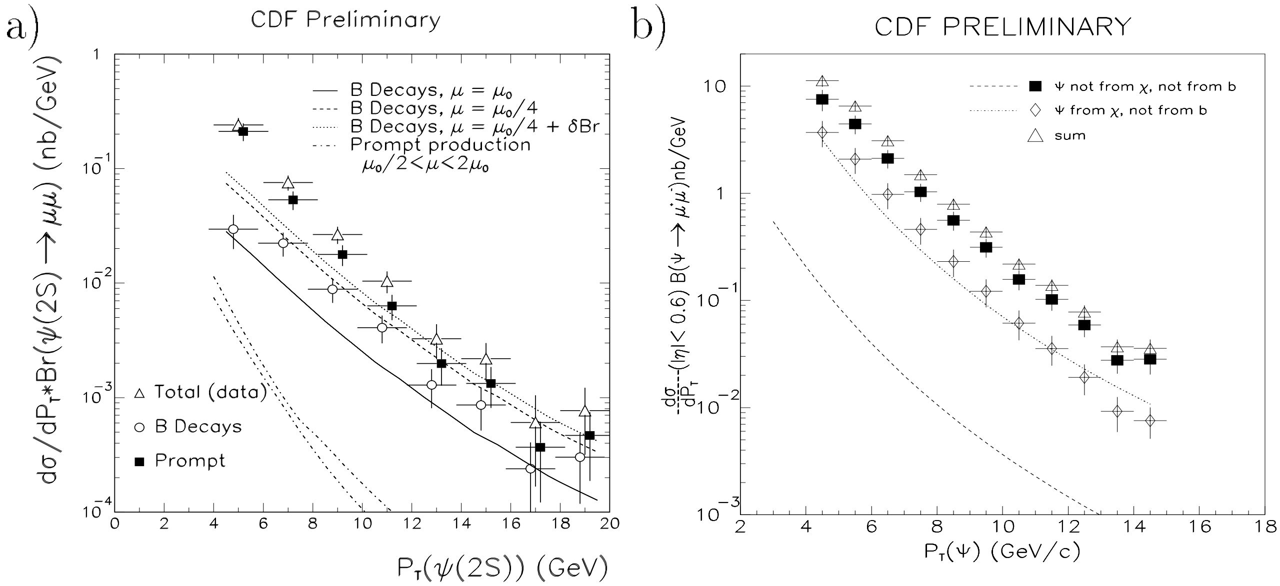


Figure 2: a) $\psi(2S)$ cross sections: B-component compared with NLO QCD[9], and prompt component compared to QCD (fusion and fragmentation)[21]. Dash-dotted lines show variation in prompt calculation with $\mu$-scale range. b) *"prompt"* (B-contribution removed) $J/\psi$ cross sections separated into "direct" and $\chi$-components along with theoretical expectations.

speculation[23,24]. One intriguing proposal is the "color-octet" mechanism[24]. Originally conceived for purely formal reasons[25], this mechanism proposes that as well as color-singlet states, color-octets are produced which become singlets by radiating soft gluons. While the color-octet is formally the same order in $\alpha_s$, it may nevertheless dominate, in part because the radiated gluons are soft. The non-perturbative octet-matrix elements are unknown, leaving the size of the cross section free. Attempts are being made to extract the matrix elements from fits to this data[15,17,24], but further tests of the octet hypothesis are needed.

## III. b-Hadron Masses

CDF is able to measure b-hadron masses quite accurately from exclusive decays containing a $J/\psi$ and charged tracks in the final state. A large sample of $J/\psi \to \mu^+\mu^-$ (80,000 in the $\sim 19$ pb$^{-1}$ for just Run Ia) is used for calibration and to study systematics[26].

B-mesons are reconstructed via the decays: $B_u^+ \to J/\psi K^+$, $B_d^0 \to J/\psi K^{*0}$, $B_s^0 \to J/\psi\phi$, with $K^{*0} \to K^+\pi^-$ and $\phi \to K^+K^-$ (and charge conjugates). The $\pi$'s and $K$'s are charged tracks with the appropriate mass assignment (i.e. no particle I.D.). Mass windows are used to select candidate particles: within $\pm 100$, $\pm 50$, $\pm 10$ MeV/c$^2$ for $J/\psi$'s, $K^{*0}$'s, and $\phi$'s. A global fit of the B-candidate is made by imposing constraints on masses ($J/\psi$, $K^{*0}$, $\phi$), secondary vertex, and pointing to the collision vertex. Decay length and $p_t$ cuts* further reduce the

*We require $p_t(K^+) > 2$, $p_t(K^{*0}) > 3$, $p_t(\phi) > 2$, and $p_t(B_{u,d}) > 8$, $p_t(B_s) > 6$ GeV/c. For the B-decay lengths: $c\tau > 100\mu m$ for $B_{u,d}$, $c\tau > 0$ for $B_s^0$. The $c\tau$ is "signed" such that if the vertex displacement vector is

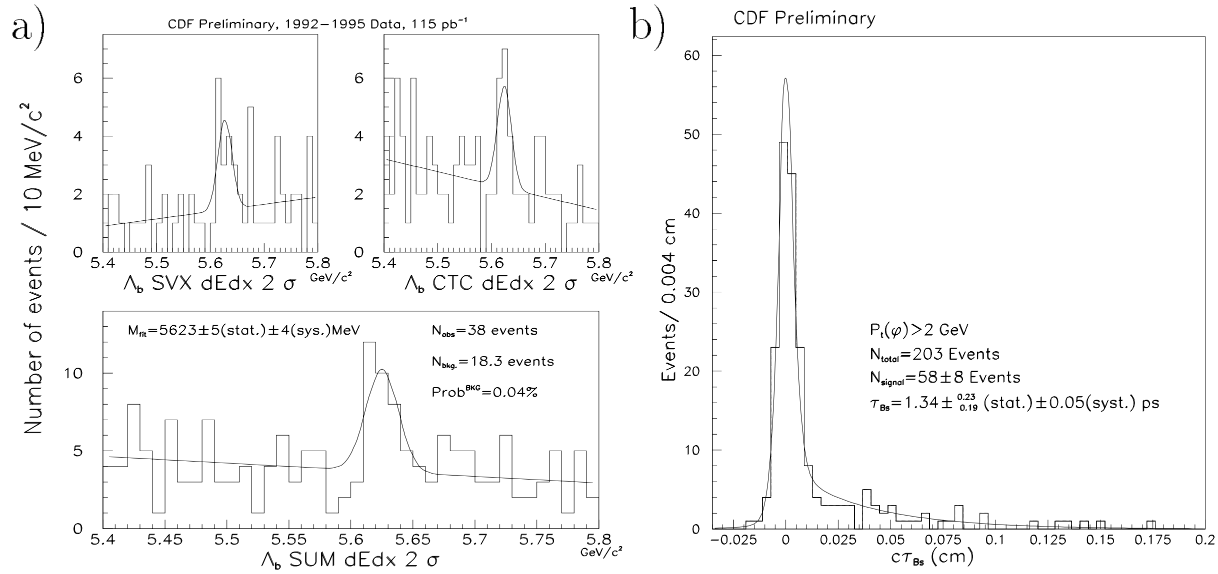


Figure 3: a) $J/\psi\Lambda$-mass distribution for "SVX" and "non-SVX" subsamples, and the total. b) $B_s^0 \to J/\psi\phi$ lifetime distribution for events within $\pm 50$ MeV/c$^2$ of the $B_s^0$-mass.

background. In 19 pb$^{-1}$ there were $147 \pm 14$ $B_u^+$'s, $51 \pm 8$ $B_d^0$'s, and $32 \pm 6$ $B_s^0$'s reconstructed, and a binned likelihood fit resulted[26] in $m(B_u^+) = 5279.1 \pm 1.7 \pm 1.4$, $m(B_d^0) = 5281.3 \pm 2.2 \pm 1.4$, $m(B_s^0) = 5369.9 \pm 2.3 \pm 1.3$ MeV/c$^2$ (statistical followed by systematic errors).

We have recently observed a signal in $\Lambda_b \to J/\psi\Lambda$ ($\Lambda \to p\pi^-$). The reconstruction mimics that used for exclusive meson decays. Charged tracks are assigned p and $\pi$ masses to reconstruct $\Lambda^0$-candidates. Candidates consistent with $K_s^0 \to \pi^+\pi^-$ are rejected, and we require the $\Lambda$ transverse decay length exceed 1.0 cm, $p_t(\Lambda) > 1.5$ GeV/c, and $p_t(J/\psi\text{-}\Lambda) > 6.0$ GeV/c. The candidates are subdivided into the two cases where both muons are reconstructed in the SVX, or not. The "SVX" candidates are required to have a proper decay length ($c\tau$) above 100 $\mu$m; the remaining candidates must have $c\tau > 0\mu$m. The background is further suppressed by the application of a $dE/dx$-cut, principally because of the presence of the low momentum proton in the signal. The $dE/dx$ as measured in the Central Tracking Chamber is required to be within $2\sigma$ of the nominal values for both the $p$ and $\pi$. In a sample of 115 pb$^{-1}$ a fit of the resulting mass distribution, Fig. 3a, yields 38 $\Lambda_b$'s over a background of 18 events. We determine the $\Lambda_b$ mass to be $5623 \pm 5 \pm 4$ MeV/c$^2$, a substantial improvement over previous measurements[27].

## IV. B-Meson Decays

Measurements of event rates for exclusive decays may also be used to obtain information on branching ratios ($Br$), or on only $\sigma \cdot Br$ when both $\sigma$ and $Br$ are unknown. We have completed[28] analysis on 19 pb$^{-1}$ for the branching ratios of $B^0 \to J/\psi K^0$, $B^0 \to J/\psi K^{*0}$, and

antiparallel to the momentum $c\tau < 0$ (see Sec. V). This may occur due to resolution and reconstruction errors.

$B^+ \to J/\psi K^{*+}$ relative to $B^+ \to J/\psi K^+$. We can express our results as absolute branching ratios by using the PDG value of $Br(B^+ \to J/\psi K^+) = 0.102 \pm 0.014\%$[29]:

$$Br(B^0 \to J/\psi K^0) = 0.115 \pm 0.023 \pm 0.017\%;$$
$$Br(B^0 \to J/\psi K^{*0}) = 0.136 \pm 0.027 \pm 0.022\%;$$
$$Br(B^+ \to J/\psi K^{*+}) = 0.158 \pm 0.047 \pm 0.027\%.$$

We have also observed $25.1 \pm 8.4$ candidates (63 $\mathrm{pb}^{-1}$) of the Cabbibo-suppressed decay $B^+ \to J/\psi \pi^+$, and determined its branching ratio relative to $J/\psi K^+$ to be $4.9^{+1.9}_{-1.7} \pm 1.1\,\%$. This compares well with CLEO's value of $5.2 \pm 2.4\,\%$[30]. CDF also has limits on a number of rare B-decays ($B \to \mu^+\mu^-,\ \mu^+\mu^- K^\pm,\ \mu^+\mu^- K^{*0}$), these however are discussed elsewhere[31].

The longitudinal polarization fractions (, $_L$/, ) can be extracted from our $B_d^0 \to J/\psi K^{*0}$ and $B_s^0 \to J/\psi \phi$ reconstructions. Such measurements help test factorization and are relevant to CP-studies[32]. We found for 19 $\mathrm{pb}^{-1}$ that , $_L$/, $= 0.65 \pm 0.10 \pm 0.04$ for the $B_d^0$ ($65 \pm 10$ events), and , $_L$/, $= 0.56 \pm 0.21^{+0.02}_{-0.04}$ for the $B_s^0$ ($19 \pm 5$ events)[32]. The $B_d^0$ result is somewhat lower than values from ARGUS ($0.97 \pm 0.16 \pm 0.15$)[33] and CLEO ($0.80 \pm 0.08 \pm 0.05$)[34], and would be easier to accommodate in the factorization hypothesis. The $B_s^0$ measurement is unique.

## V. B-Meson Lifetimes

B-lifetimes are governed by the details of the decay mechanisms beyond the spectator model. In contrast to the D-mesons, one expects small ($\approx$ 5-10%) differences between $B^+$ and $B^0$, thereby demanding precise measurements. We use our Si-$\mu$vertex detector to measure decay vertices for both exclusive reconstructions based on $J/\psi$-decays and semileptonic decays.

B-mesons are fully reconstructed via $B_{u,d} \to \psi K$ and $B_s \to J/\psi \phi$, where $\psi$ is either the 1S or 2S state, and $K$ is $K^\pm$, $K_s^0$, or $K^*(892)$. The reconstruction is very similar to the mass measurements but with cuts optimized for lifetimes. We measure the (signed) transverse decay length ($L_{xy}$) of the fully reconstructed meson to obtain the proper decay length ($c\tau$):

$$c\tau = L_{xy} \frac{m(B)}{p_t(B)}, \quad L_{xy} = \frac{(\vec{x}_{2ndry} - \vec{x}_{Primary}) \cdot \vec{p_t}(B)}{p_t(B)}$$

and fit the $c\tau$ distributions to extract the lifetimes[35].

For the $B_{u,d}$ (68 $\mathrm{pb}^{-1}$) a signal region ($\pm 30$ MeV/c$^2$ around the $B_{u,d}$) and sidebands (60 to 120 MeV/c$^2$ away) are chosen. The background is determined by fitting the sideband region to a Gaussian with exponential tails. The signal region is then a weighted average of this background shape and an exponential (for B-decays) convoluted with a Gaussian (for resolution). The size of the signal and background is further constrained by the amount in the mass distribution. The results of the lifetime fits, and lifetime ratio, is given in Table 1.

The statistics for the $B_s$ is much lower (even for $\sim$ 100 $\mathrm{pb}^{-1}$) so that we do not separate the sideband $c\tau$ distribution for the background; instead we do a simultaneous (unbinned)

Table 1: B-meson lifetimes in psec (first error is statistical, second systematic).

| Lifetime | Exclusive | Semi-Exclusive |
|---|---|---|
| $\tau_u^+$ | $1.68 \pm 0.09 \pm 0.06$ | $1.56 \pm 0.13 \pm 0.06$ |
| $\tau_d^0$ | $1.64 \pm 0.11 \pm 0.06$ | $1.54 \pm 0.08 \pm 0.06$ |
| $\tau_u^+/\tau_d^0$ | $1.02 \pm 0.09 \pm 0.01$ | $1.01 \pm 0.11 \pm 0.02$ |
| $\tau_s^0$ | $1.34 \pm {}^{0.23}_{0.19} \pm 0.05$ | $1.42 \pm {}^{0.27}_{0.23} \pm 0.11$ |

log-likelihood fit of the mass (Gaussian + flat background) *and* the $c\tau$ (signal: exponential convoluted with Gaussian; background: Gaussian with positive/negative exponential tails) distributions[36]. The $c\tau$ distribution is shown in Fig. 3b, and the lifetime given in Table 1.

We have also applied the approach of utilizing semi-exclusive decays (19 pb$^{-1}$): $B_{u,d,s} \rightarrow \ell D X$, where $\ell = e$, $\mu$, and the "$D$" may be reconstructed in a cone around the lepton by:

$$D^0 \rightarrow K^-\pi^+$$

$$D^{*+} \rightarrow D^0\pi^+_{soft}; \quad D^0 \rightarrow K^-\pi^+, \quad \text{or} \quad \rightarrow K^-\pi^+\pi^0_{lost}, \quad \text{or} \quad \rightarrow K^-\pi^+\pi^+\pi^-$$

$$D_s \rightarrow \phi\pi, \quad \phi \rightarrow K^+K^-$$

The B-decay vertex ($L_{xy}$) is determined from the intersection of the lepton and $D$ trajectories. The exact $\beta\gamma$-factor to convert $L_{xy}$ into $c\tau$ is unknown because of the undetected particles. This obstacle is overcome by applying the average correction factor needed to go from $p_t(D\ell)$ to $p_t(B)$ as determined by Monte Carlo. The $\ell^- D^0$ channel is about 85% $B^-$, and $\ell^- D^{*+}$ is about 90% $\bar{B}^0$. This cross talk is modeled by Monte Carlo, and we find the lifetimes from the global fit, given in Table 1[37], are insensitive to its precise value. In a similar analysis already published[36], 76 $B_s^0 \rightarrow \ell D_s$ candidates were fit, with the lifetime also listed in Table 1.

Our results compare well, both in value and sensitivity, with other experiments in a recent review[27]. The world average of the $B_u^-/B_d^0$-lifetime ratio is consistent with 1.0, and is down to $\sim 4\%$ uncertainty.

## VI. $B^0$-$\bar{B}^0$ Mixing

As is the case in the $K^0$-system, higher order weak interactions are responsible for $B^0 \leftrightarrow \bar{B}^0$ transitions which result in mass eigenstates ($B^0_{Heavy}$ & $B^0_{Light}$) that are a mixture of weak eigenstates ($B^0$ & $\bar{B}^0$). A consequence of this mixing is that a $B^0$ (produced at time $t = 0$) will turn into a $\bar{B}^0$ (at time $t$) with a probability:

$$\mathcal{P}(B^0[0] \rightarrow \bar{B}^0[t]) = \frac{e^{-t/\tau}}{2\tau}[1 - \cos(\Delta m t)]$$

where $\tau$ is the (average) B-lifetime and $\Delta m = m(B^0_H) - m(B^0_L)$. The time-dependence can be integrated out to yield the overall probability for a produced $B^0$ to be observed as a $\bar{B}^0$:

$$\mathcal{P}(B^0 \rightarrow \bar{B}^0) \equiv \chi = \frac{x^2}{2(1+x^2)}$$

with $x \equiv \Delta m/\Gamma$, and $\Gamma$ the (average) width.

### Time-Integrated Mixing

Mixing in the B-meson systems was first measured by exploiting the charge correlation in semileptonic b-decays[38], the technique we follow here. Given that $b$ and $\bar{b}$ are produced in pairs, and that $b \rightarrow \ell^- + c$ while $\bar{b} \rightarrow \ell^+ + \bar{c}$, the ratio of the number of like-sign (LS) to opposite-sign (OS) dileptons is determined by $\chi$, i.e.

$$R \equiv \frac{LS}{OS} = \frac{\mathcal{P}(b;\bar{b}\rightarrow b) + \mathcal{P}(b\rightarrow \bar{b};\bar{b})}{\mathcal{P}(b\rightarrow \bar{b};\bar{b}\rightarrow b) + \mathcal{P}(b;\bar{b})} = \frac{(1-\chi)\chi + \chi(1-\chi)}{\chi^2 + (1-\chi)^2} = \frac{2\chi(1-\chi)}{\chi^2+(1-\chi)^2}$$

Experimentally the situation is more complex. Since both $B_d^0$ and $B_s^0$ are produced and mix, the R-value is determined by the average $\bar{\chi} = F_d\chi_d + F_s\chi_s$, where $F_{d(s)}$ is the average fraction of $B^0_{d(s)}$ produced (including the fact that other, non-mixing, b-hadrons may be present).

The analysis is further complicated by sequential ($b \rightarrow c \rightarrow \ell^+$) decays, direct $c\bar{c}$ production, and the fake lepton backgrounds. These contributions modify the sign ratio to become:

$$R = \left(\frac{LS}{OS}\right)_{meas} \frac{1 - F_{\ell^\pm\ell^\pm}(LS)}{1 - F_{\ell^\pm\ell^\mp}(OS)} = \left(\frac{2\bar{\chi}(1-\bar{\chi}) + [\bar{\chi}^2 + (1-\bar{\chi})^2]f_s}{\bar{\chi}^2 + (1-\bar{\chi})^2 + 2\bar{\chi}(1-\bar{\chi})f_s + f_c}\right)$$

where $(LS/OS)_{meas}$ is the experimentally measured ratio, $F_{\ell^+\ell^-}$ are the fractions of fake and decay-in-flight leptons in the respective signed samples, $f_s$ is the ratio of sequential to direct decays ($b \rightarrow c \rightarrow \ell$ to $b \rightarrow \ell c$), and $f_c$ is the ratio of $c\bar{c} \rightarrow \ell\ell$ to $b\bar{b} \rightarrow \ell\ell c\bar{c}$.

CDF has results in both the $e\mu$ and $\mu\mu$ channels. For $e\mu$ events with $p_t(\ell) > 3.0$ GeV/c, lepton-$p_t$ above 1.5 GeV/c *relative* to an associated jet ($p_t > 0.5$ GeV/c tracks in $\Delta R < 0.8$ cone), and $e\mu$-transverse opening angle above 45°, we found 1710 opposite-sign and 861 like-sign pairs yielding† $\bar{\chi} = 0.130 \pm 0.010 \pm 0.009$. Assuming the usual values of $F_d = 0.391$ and $F_s = 0.117$[29], we show in Fig 4a the relation between the two $\chi$-components. Also portrayed is the ARGUS[39] and CLEO[40] average, as well as the range allowed by the CKM-matrix.

By a similar analysis in the $\mu\mu$ channel (17 pb$^{-1}$) we find $\bar{\chi} = 0.118 \pm 0.021 \pm 0.026$. This result is not as precise as the $e\mu$ because of the lower statistics that result from the tighter $\mu$-selection. Both results compare well with other experiments[41], and will substantially improve with the full statistics and further systematic studies.

### Time-Dependent Mixing

A $\chi$-type analysis was the only means of measuring B-mixing until the advent of $\mu$vertex detectors at high energy colliders. As was first demonstrated by ALEPH[42], observation of

†Using $f_s = 0.136 \pm 0.023$, and $f_c = 0.007 \pm 0.011$ as determined from Monte Carlo; $F_{e^\pm\mu^\pm} = 0.396 \pm 0.042$, and $F_{e^\pm\mu^\mp} = 0.255 \pm 0.026$ derived from data by releasing lepton identification cuts.

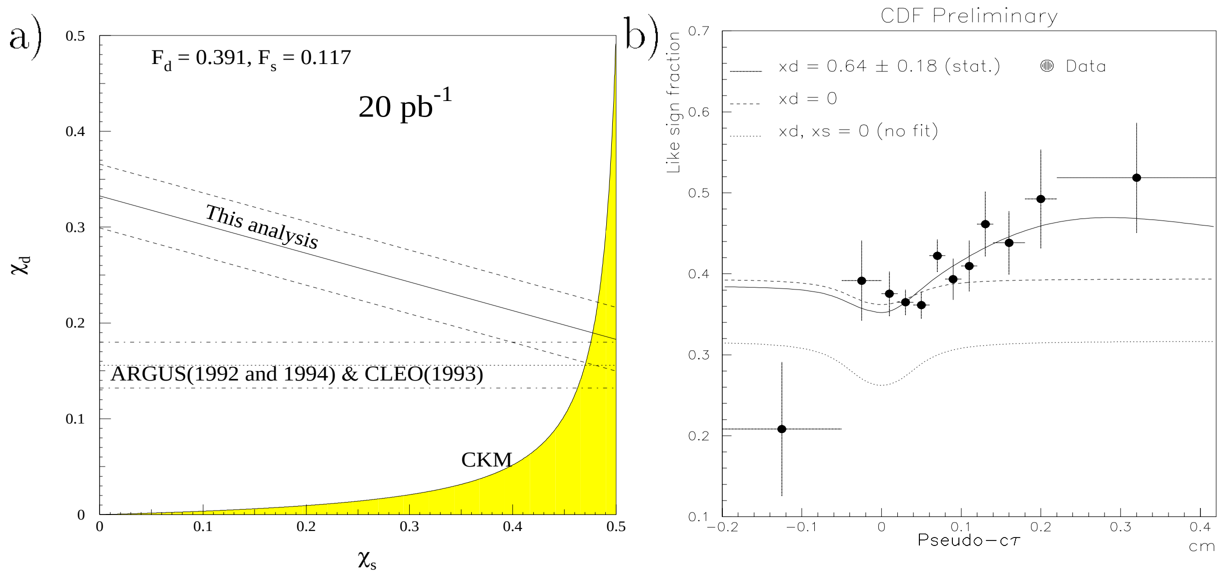


Figure 4: a) CDF $\bar{\chi}$ result along with that of ARGUS and CLEO, and the Standard Model CKM limits. b) Time dependence of the like-sign fraction (see text for a description).

the time-dependence of the mixing oscillation enables one to extract $\Delta m_u$.[‡] We use a dimuon sample with $m_{\mu\mu} > 5$ GeV/c$^2$ (suppressing $b \to c\mu X \to \mu\mu X$), in which the relative sign determines the mixing. The time dependence is established by searching for "D"-decays, and obtaining a $\mu$D-vertex for the B. The "D" is simply an identified secondary vertex close to one of the muons. The $L_{xy}$ of this vertex is used to obtain the pseudo-$c\tau$ of the B-decay (as in the semi-exclusive lifetime analysis). Background (especially $b \to c \to \ell$) is further reduced by requiring the $p_t$ of the lepton relative to the "$D$" be greater than 1.3 GeV/c.

Analysis of 20 pb$^{-1}$ resulted in 1516 LS and 2357 OS events, for which we plot in Fig. 4b the LS fraction ($N_{LS}/(N_{LS}+N_{OS})$) as a function of pseudo-$c\tau$. The first quarter cycle of the oscillation is clearly visible. To extract $\Delta m_d$ we must model the backgrounds. A 3-component ($b \to \mu$, $b \to c \to \mu$, and $c \to \mu$) fit of the relative $\mu$-D $p_t$ distribution found a $\sim 1\%$ charm background. The fake muon fraction is estimated to be $10 \pm 3.5\%$ by a 2-component fit of muon impact parameters. The relative fraction (and effects) of $b \to c \to \mu$ are determined by Monte Carlo (average fraction of sequentials: $15.1 \pm 0.6\%$ vertex side; $19.4 \pm 0.6\%$ away side), and are the dominant systematic. Monte Carlo was also used to model the effects of the $c\tau$ resolution.

For the fit we let $\chi_s = 0.5$, the fractions of $B_d^0$ and $B_s^0$ are free parameters but constrained to be consistent with LEP[43)] ($37 \pm 3\%$, and $15 \pm 4\%$ respectively); and we obtain a $\Delta m_d$ of $0.44 \pm 0.12 \pm 0.14$ psec$^{-1}$. The fit is drawn in Fig. 4b as the solid line. The dashed line shows the result if $B_u^0$-mixing were zero but still full $B_s^0$-mixing: the oscillation is gone ($B_s^0$ oscillates too fast to be seen), and while the like-sign fraction matches the data around zero $c\tau$, it is below the

[‡]The $B_s^0$ oscillation is also present. However its mixing is so large, and the oscillation so rapid, that its effect is only to add a constant contribution with our current sensitivity.

data at large $c\tau$, in clear disagreement. If there were no mixing at all ($\chi_d = \chi_s = 0$) the like-sign ratio shifts down to the dotted line. (The valley around zero is due to the $c\tau$-dependence of the residual sequential decays). The result is in good agreement with LEP[41].

## VII. Summary

Various facets of particle physics have been studied via b-quarks at CDF. From QCD tests of heavy quark production, masses, decay characteristics, lifetimes, to $B^0$-mixing. Our results are competitive with other experiments even though only partial data sets are analyzed. Significant improvements are to be expected in most analyses for both statistics and refinement of systematic errors. New topics are also under study. For example, soon after this conference a sample of $\Lambda_b \to \Lambda_c^+ \ell X$ events were used to measure the $\Lambda_b$-lifetime ($1.33 \pm 0.16 \pm 0.07$ ps), as well as the production fraction ($f(b \to \Lambda_b) Br(\Lambda_b \to \Lambda_c^+ e^- X) Br(\Lambda_c^+ \to pK^-\pi^+) = 9.5 \pm 2.5^{+4.4}_{-4.0} \times 10^{-4}$). On the more distant horizon, CDF is in the process of upgrading for the Main Injector run before the close of the millennium. Peak luminosities of $\sim 2 \times 10^{32}$ cm$^2$/s and integrated data sets of order 2 fb$^{-1}$ are expected; with which a high priority will be CP-violation studies[44].

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